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INTEGRATED ARRAY AND 3-COMPONENT PROCESSING USING A SEISMIC "MICROARRAY"

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Integrated array and 3-component processing using a seismic "microarray"

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A "microarray" as defined in this paper is modeled on a subgeometry of the NORESS array (Mykkeltveit et al., 1990), and comprises a 3-component center seismometer surrounded by 3 closely spaced vertical-component sensors deployed over a typical aperture of 0.3 km. Analysis of five days of continuous data has shown that such a system combines the benefits of array and 3-component processing in providing reliable automatic detection, phase identification and location of weak seismic events at local and regional distances. The data processing has comprised a) multiple-band filtering, b) coherent and incoherent beamforming, c) STA/LTA threshold detection, d) broadband frequency-wavenumber (f-k) analysis and e) automatic phase association and event location. Using vertical components only, broadband f-k array analysis enables correct phase identification (P-type og S-type phase) in 95 per cent of the cases, and gives S-wave azimuths with a root-mean-square (RMS) deviation of 13.9 degrees from the estimates of the full NORESS array. It is particularly significant that the small array eliminates the need for introducing particle motion

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models, which creates ambiguities in 3-component analysis of secondary phases when interfering SH and SV phases occur. P-phase azimuths are estimated using integrated array and 3-component f-k analysis, and have an RMS deviation relative to NORESS of only 9.6 degrees. Compared to the full NORESS array, the P-wave detection capability is good for events with epicenters within 500 km of the station, but for greater distances the performance is significantly reduced. The S-phase detection capability is enhanced by incoherent beamforming of the horizontal channels, and approaches that of NORESS at all distances. A considerable reduction in the detector false alarm rate is achieved by imposing constraints on the estimates of apparent velocity obtained from the f-k analysis before accepting a detected phase.

Preface

Under Contract No. F49620-C-89-0038, NTNF/NORSAR is conducting research within a wide range of subjects relevant to seismic monitoring. The emphasis of the research program is on developing and assessing methods for processing of data recorded by networks of small-aperture arrays and 3-component stations, for events both at regional and teleseismic distances. In addition, more general seismological research topics are addressed.

Each quarterly technical report under this contract presents one or several separate investigations addressing specific problems within the scope of the statement of work. Summaries of the research efforts within the program as a whole are given in annual technical reports.

This Scientific Report No. 9 presents a manuscript entitled "Integrated array and 3-component processing using a seismic "microarray", by T. Kværna and F. Ringdal.

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INTRODUCTION

In order to handle the large data volumes produced by modern digital seismic networks, a high degree of automated processing is essential. A case in point is the newly established network of regional arrays and three-component stations in northern Europe (Harjes, 1990; Mykkeltveit and Paulsen, 1990; Mykkeltveit et al., 1990; Uski, 1990). Current methods allow for successful real-time processing of the arrays within this network (Ringdal and Kværna, 1989; Bache et al., 1990), while the algorithms available for three-component data processing, as discussed in the following, do not yet meet the criteria required for real-time operation.

The problems remaining to be solved are primarily those of automatic phase identification and azimuth estimation. Such information is essential for successful automatic phase association and location of seismic events. It has been demonstrated that polarization analysis can provide P-wave azimuth estimates with good accuracy from a single three-component station (Plešinger et al., 1986; Magotra et al., 1987; Christofferson et al., 1988; Jurkevics, 1988; Ruud et al., 1988). Using SH and SV particle motion models, some success has also been reported in determining azimuth from S and Lg phases, although there is often a 90 or 180 degree ambiguity in the resulting estimates (Magotra et al., 1987; Jurkevics, 1988).

These efforts notwithstanding, the fundamental problem of phase identification using three-component data has not been satisfactorily solved. According to Jepsen and Kennett (1990) it is possible to identify P-waves and fundamental mode Rayleigh waves (Rg) from three-component data alone, but classification of other wave types appears to be much less reliable. Their results are all derived from offline analysis of high signal-to-noise ratio (SNR) recordings, and thereby give an upper bound on what can be achieved by automated procedures. Our own experience, based on several years with routine polarization analysis of the three-component elements within the NORESS array in southern Norway, confirms this. Thus, we have found that a high degree of rectilinearity together with steep incidence angles, which in theory would indicate the presence of a P-phase, is quite often also seen for S and Lg phases, and even for noise bursts. To further complicate the situation, numerous P-phases are observed that do not meet the theoretically expected polarization characteristics.

Array developments

Small-aperture arrays of the NORESS type have proved to be very effective in processing of regional as well as teleseismic signals (Mykkeltveit et al., 1990). Their primary features are:

- Significant SNR gains at high frequencies.
- Reliable phase identification (P-type versus S-type phases).
- Precise azimuth estimates of all phases.

While the accuracy of NORESS azimuth estimates can be as good as ± 1 degree for well calibrated regions (Kværna and Ringdal, 1986), the uncertainty of uncalibrated regions is often of the order of 10 degrees or more, due to lateral inhomogeneities near the receivers (Mykkeltveit et al., 1990). In practical schemes for automatic phase association (e.g., Mykkeltveit and Bungum, 1984), a tolerance of 30 degrees in azimuth deviation from the true value is often assumed. Given that the tolerance limits of the azimuth estimates for phase association purposes are much less restrictive than the optimum array capability, a natural question is whether a smaller array can achieve reliable phase identification as well as an acceptable uncertainty for the azimuth estimates.

In this paper we address this question, and we have chosen to evaluate the smallest such array available to us; the NORESS A-ring geometry (Fig. 1). This "microarray" comprises a center three-component seismometer A0, surrounded by three vertical-component sensors A1-A3. The diameter is 300 meters, i.e. a factor of 10 less than

NORESS, and the microarray thus spans an area only 1% of that of the full NORESS array.

We demonstrate in this paper that this very small array shows a remarkable performance in distinguishing betweeen regional P and S-phases and in obtaining reliable azimuth estimates for all phase types. Our conclusion is that supplementing three-component stations with a small triangular array would to a large extent alleviate the problems now encountered in automatic three-component analysis.

Data analysis

We conducted automatic detection processing and post-detection analysis of data from the A-ring microarray for a period of 5 days (22-26 October 1990). The detection processing was conducted using standard array processing techniques as described by Mykkeltveit et al. (1990). A STA/LTA detector was applied to a set of coherent and incoherent filtered beams (Mykkeltveit and Bungum, 1984; Ringdal et al., 1975). Parameters on filter bands, beam configuration and detection thresholds are given in Table 1. The post-detection processing included broadband f-k array analysis (Esmersoy et al., 1985; Kværna and Doornbos, 1986) of each detected signal using the 4 vertical-component sensors. The resulting apparent velocity estimates were used to classify the detected signal as a P-type or S-type phase. For each P-phase, we subsequently carried out polarization analysis as well as integrated array and 3-component f-k analysis (using a P-wave particle motion model), applying the same methodology.

Briefly, this methodology is summarized as follows: We introduce the covariance matrix C as a function of slowness s by phase shifting the signals:

$$C_{nm}(\mathbf{s}) = \int_{\omega_1}^{\omega_2} F_n(\omega, \mathbf{s}) F_m^*(\omega, \mathbf{s}) \frac{d\omega}{2\pi} \qquad (1)$$

where

$$F_n(\omega, \mathrm{s}) = F_n(\omega)\exp(i\omega \mathrm{s}\cdot \mathrm{x}_n), \tag{2}$$

$F_n(\omega)$ is the Fourier spectrum at channel n, and ω_1 and ω_2 define the frequency band for analysis. The normalized response is given by

$$P(\mathbf{s}) = \mathbf{g}^{\dagger}\mathbf{C}\mathbf{g}/\{|\mathbf{g}|^2 tr\mathbf{C}\} \tag{3}$$

where $\mathbf{g}$ is the predicted displacement vector for slowness $\mathbf{s}$.

The method can be applied either to a three-component station or to an array comprising any combination of single-component and three-component stations. Thus for an array of single component seismometers: $\mathbf{g}^{\dagger} = (1, \cdots, 1)$. For a three-component station: $\mathbf{g}^{\dagger} = (g_X, g_Y, g_Z)$ (i.e., the displacement vector), and for an array of three-component seismometers: $\mathbf{g}^{\dagger} = (\mathbf{g}_1^{\dagger}, \cdots, \mathbf{g}_N^{\dagger})$ with $\mathbf{g}_n^{\dagger} = (g_{nX}, g_{nY}, g_{nZ})$ denoting the displacement vector at site n. The slowness estimate of the incoming wave is defined by the maximum of the normalized response.

To obtain a data base against which to evaluate our results, we extracted all seismic phases detected by the full NORESS array and associated to regional events for the 5-day period. The generalized beamforming procedure (Ringdal and Kværna, 1989) and the results from Intelligent Monitoring System (IMS) processing (Bache et al., 1990) were used in order to validate these reference events. P-coda detections and multiple S-phases were ignored, so that each event provided a maximum of 3 phases (P, S and Lg). These phases were then matched to the detection lists produced from the A-ring microarray, and the apparent velocity and azimuth estimates were compared.

Phase identification

Figure 2 shows the apparent velocity estimates using the vertical sensors of the microarray for P-phases (circles) and S-phases (asterisks) for the reference data set.

The separation is better than 95 per cent, which implies that even this very small array is able to provide correct phase identification automatically and with high confidence. We emphasize that this success rate is achieved in a completely automated mode using only the intrinsic features of each detected phase, most of which have very low SNR. Even further improvements would clearly be possible by off-line analysis and visual inspections of the traces.

P-wave azimuths

Figure 3 compares P-wave azimuths estimated by the full NORESS array and the vertical components of the microarray using broadband f-k analysis in both cases. The estimates are quite consistent with an RMS deviation of 13.7 degrees. A corresponding plot for P-waves analyzed from the three-component seismometer A0 is given in figure 4, and shows a similar amount of scatter, with an RMS deviation of 14.3 degrees. Figure 5 shows a corresponding plot using P-phase azimuth estimates derived from integrated array and three-component analysis. In this case the RMS deviation is considerably lower, 9.6 degrees, and all of the deviations are well within a tolerance limit of 30 degrees. The improvements relative to a single three-component station are particularly significant at low signal-to-noise ratios.

S-wave azimuths

Figure 6 compares azimuths of S-type phases estimated by the microarray (using the vertical components only) and the full NORESS array. Again, the correspondence is quite good, with an RMS deviation of 13.9 degrees. This implies that it is possible to use the algorithm described by Mykkeltveit and Bungum (1984) to achieve automatic regional phase association and event location using this microarray. Note that in the case of S-phases, we have not been able to obtain useful azimuth information from three-component or integrated processing, but it is of course possible that such information could be extracted in certain cases, given that the phase first has been identified as S or Lg.

Detectability

Figures 7 and 8 illustrate the P and S-wave detectability of the microarray as a function of NORESS SNR. From Figure 7, it is seen that all P-phases with SNR > 20 dB (i.e., STA/LTA > 10 at NORESS) have been detected. At distances below 500 km, several events of relatively low SNR at NORESS has also microarray detections. This is due to the high signal frequencies which cause the full array SNR gains of these phases to be less than the theoretical $\sqrt{N}$, whereas the microarray still retains some SNR gain. At distances above 500 km, the superiority of the full NORESS array becomes apparent.

In Figure 8 it is seen that the microarray is close to matching NORESS S-phase detectability at all distances. This is because the horizontal components of the A0 three-component system provide quite efficient detection of S and Lg phases, in particular when added incoherently to the vertical component. The full array does not hav the same SNR gain for secondary phases as it does for P-phases, because of less signal coherency and (in particular) coherent "noise" caused by the P coda. Thus, relative to NORESS, the excellent secondary phase detection of the microarray is noteworthy.

False alarm consideration

In practical operation of any seismic surveillance system, the problem of false detections is very important. This is especially the case if the real-time detection is operated at a low detection threshold, and it is essential to be able to identify false alarms at as early a stage as possible.

To address this problem, we have analyzed in detail all the microarray detections for one day (24 October 1990). The results are presented in Table 2, again with NORESS results as a reference. From this table, it is seen that 132 of the 153 detections (86%) were correctly classified using the broadband f-k analysis applied to the microarray data. Of these 153 detections, 41 were P, 41 S (or Lg) and 71 noise (i.e., detections with low apparent velocity). Note that P coda detections were counted as P and that S coda detections were counted as S in these statistics. None of the 41 phases which (according to NORESS) were of the P type were misclassified by the microarray. Of the 41 S-phases, 4 were misclassified as P. Out of 71 noise detections, 8 were given P-phase velocities and 9 were given S-phase velocities when using the microarray. However, it is possible that some of these "noise" detections are in fact real P or S phases for events at very local distance.

These statistics must be considered satisfactory. In fact, it appears that the SNR threshold for the microarray detector could be lowered, and still produce a reasonable false alarm rate.

CONCLUSIONS

The problems encountered when using a three-component system in a real-time automatic processing environment appear to be effectively alleviated by supplementing the 3-component system with a very small 3-element array with a typical aperture of 300 meters. Based on this study of the NORESS A-ring microarray, we conclude that:

- Reliable phase identification (P type versus S-type phases) can be achieved for more than 95% of the detections applying broadband f-k analysis to the four vertical instruments.
- Azimuth estimates, with accuracy generally within 30 degrees, can be obtained both for P and S-phases. The accuracy of the P-wave azimuth estimates using integrated array and 3-component f-k analysis is particularly good, showing an RMS deviation from NORESS estimates of only 9.6 degrees.

- Good regional P-phase detectability can be obtained from this microarray out to 500 km epicentral distance. At greater distances, P-wave detectability relative to that of the full NORESS array deteriorates sharply.
- Detectability of S-phases is excellent at all distances, and comes close to matching that of the full NORESS array.
- The microarray f-k analysis makes it possible to isolate the majority of the noise detections, giving an acceptable false alarm rate in the automatic processing.

It is of course important to investigate whether the results obtained here can be achieved in other geological and geographical environments, e.g., by analyzing similar data for other existing arrays (ARCESS, GERESS, FINESA). It would also be of interest to conduct network detection and location experiments using such microarrays.

A microarray of the type decribed in this paper is especially suited for processing high signal frequencies. In fact, one might consider a much denser sensor deployment within the typical microarray aperture, with the aim to conduct array processing at frequencies above 20 Hz. This would of course require a higher sampling rate than the 40 Hz currently used at NORESS. Array processing at these frequencies would be of particular interest in the context of developing methods for monitoring cavity decoupled explosions, which might have significant signal energy in this frequency band.

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Coherent beams					
Beam	Apparent vel.	Azimuth	Filter band	Configuration	Threshold
NZ01	∞	0.0	0.5- 1.5	A0z,A1z,A2z,A3z	4.0
NZ02	∞	0.0	1.0- 2.0	A0z,A1z,A2z,A3z	3.7
NZ03	∞	0.0	1.0- 3.0	A0z,A1z,A2z,A3z	3.7
NZ04	∞	0.0	1.5- 2.5	A0z,A1z,A2z,A3z	3.5
NZ05	∞	0.0	1.5- 3.5	A0z,A1z,A2z,A3z	3.5
NZ06	∞	0.0	2.0- 3.0	A0z,A1z,A2z,A3z	3.5
NZ07	∞	0.0	2.0- 4.0	A0z,A1z,A2z,A3z	3.5
NZ08	∞	0.0	2.5- 4.5	A0z,A1z,A2z,A3z	3.5
NZ09	∞	0.0	3.0- 5.0	A0z,A1z,A2z,A3z	3.5
NZ10	∞	0.0	3.5- 5.5	A0z,A1z,A2z,A3z	3.7
NZ11	∞	0.0	4.0- 8.0	A0z,A1z,A2z,A3z	3.7
NZ12	∞	0.0	5.0-10.0	A0z,A1z,A2z,A3z	3.7
NZ13	∞	0.0	8.0-16.0	A0z,A1z,A2z,A3z	4.0
Incoherent beams					
Beam	Apparent vel.	Azimuth	Filter band	Configuration	Threshold
NA01	∞	0.0	0.5- 1.5	A0z,A0n,A0e	2.7
NA02	∞	0.0	1.0- 2.0	A0z,A0n,A0e	2.6
NA03	∞	0.0	1.0- 3.0	A0z,A0n,A0e	2.5
NA04	∞	0.0	1.5- 2.5	A0z,A0n,A0e	2.5
NA05	∞	0.0	1.5- 3.5	A0z,A0n,A0e	2.5
NA06	∞	0.0	2.0- 3.0	A0z,A0n,A0e	2.6
NA07	∞	0.0	2.0- 4.0	A0z,A0n,A0e	2.8
NA08	∞	0.0	2.5- 4.5	A0z,A0n,A0e	3.4
NA09	∞	0.0	3.0- 5.0	A0z,A0n,A0e	3.5
NA10	∞	0.0	3.5- 5.5	A0z,A0n,A0e	2.8
NA11	∞	0.0	4.0- 8.0	A0z,A0n,A0e	2.5
NA12	∞	0.0	5.0-10.0	A0z,A0n,A0e	2.5
NA13	∞	0.0	8.0-16.0	A0z,A0n,A0e	2.8

TABLE 1. Parameters used for the microarray detector experiment

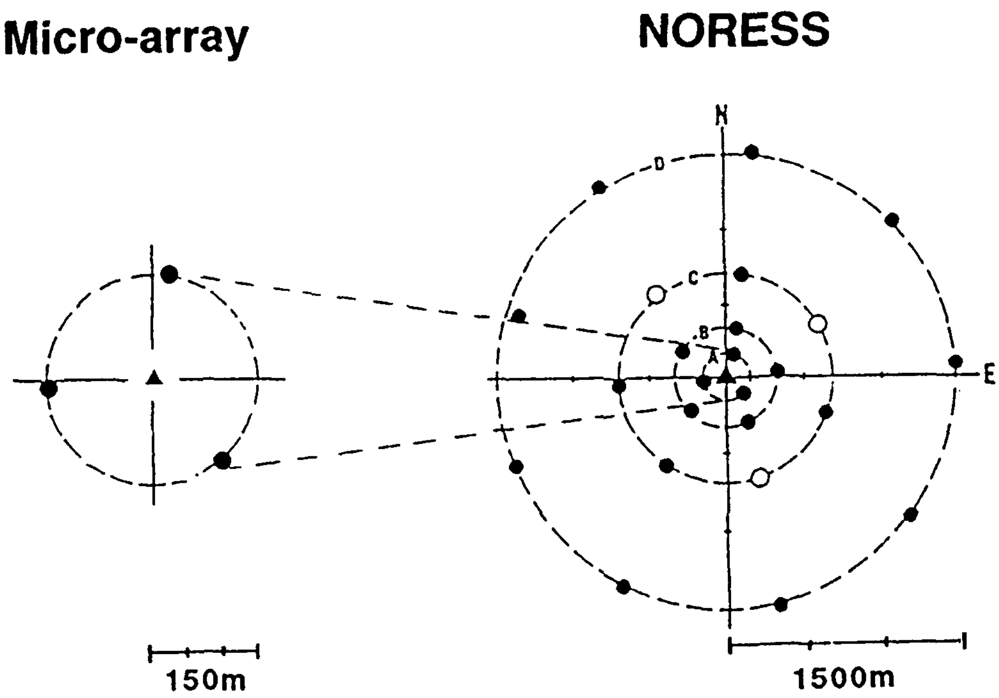
Table 2

	Classified as:		
Correct phase id	P (vel>6 km/s)	S or Lg (3.4<vel≤6 km/s)	Noise (vel≤3.4 km/s)
P	41	0	0
S or Lg	4	37	0
Noise	8	9	54

Total phases detected by the microarray detector: 153

Total phases correctly classified: 132 (86%)

TABLE 2. Statistics of detected phases for the microarray for a 24-hour period. The phases are classified based on estimated apparent velocities applying broadband f-k to the vertical components of the microarray, and "correct" phase identification is based on f-k results from the full NORESS array.



Legend:

- ● Vertical short period
- ○ 3-component short period
- ▲ 3-component broad band and 3-component short period

FIG. 1. Geometry of the NORESS array and of the A-ring geometry used in this study.

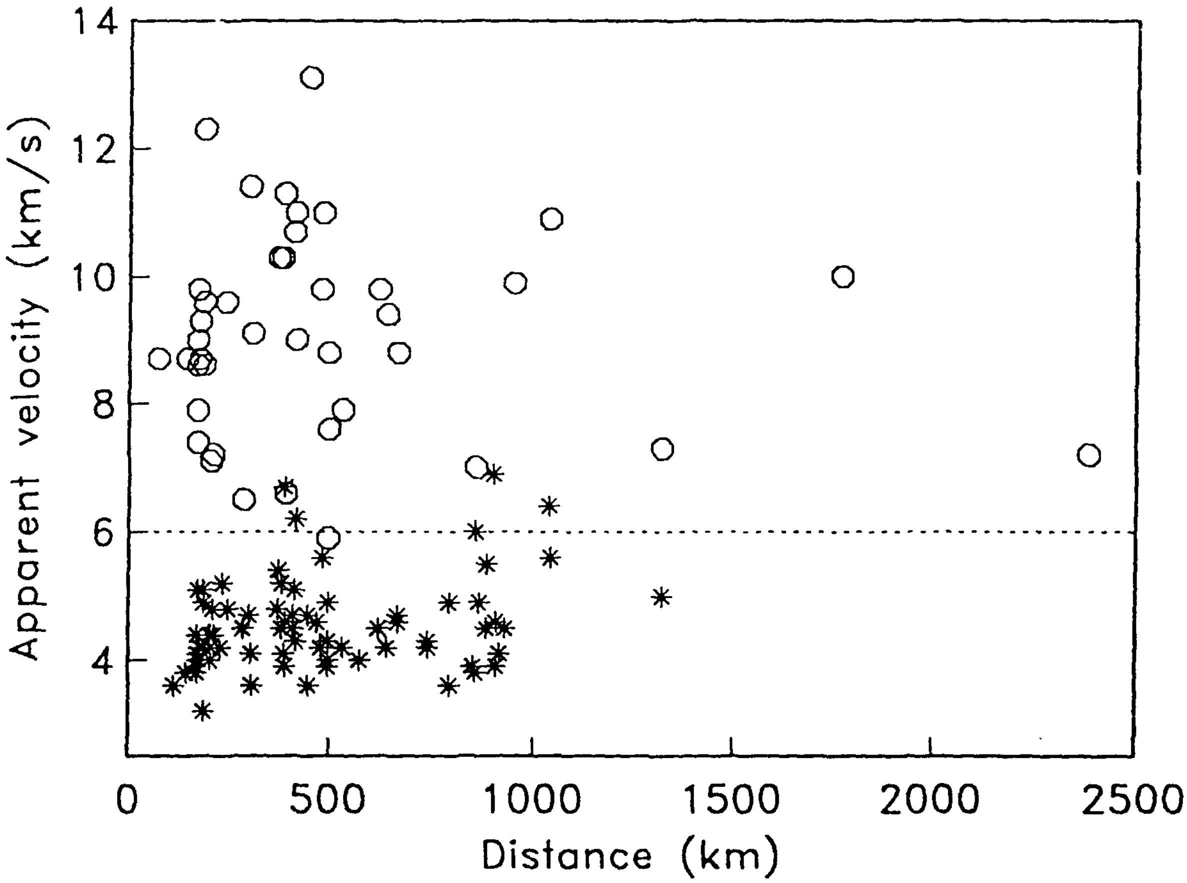


FIG. 2. Estimated apparent velocities from applying broadband frequency-wavenumber (f-k) analysis to vertical components of the A-ring microarray for detected P-phases (circles) and S-phases (asterisks). Note that the phases can be identified from the apparent velocity with more than 95 per cent accuracy.

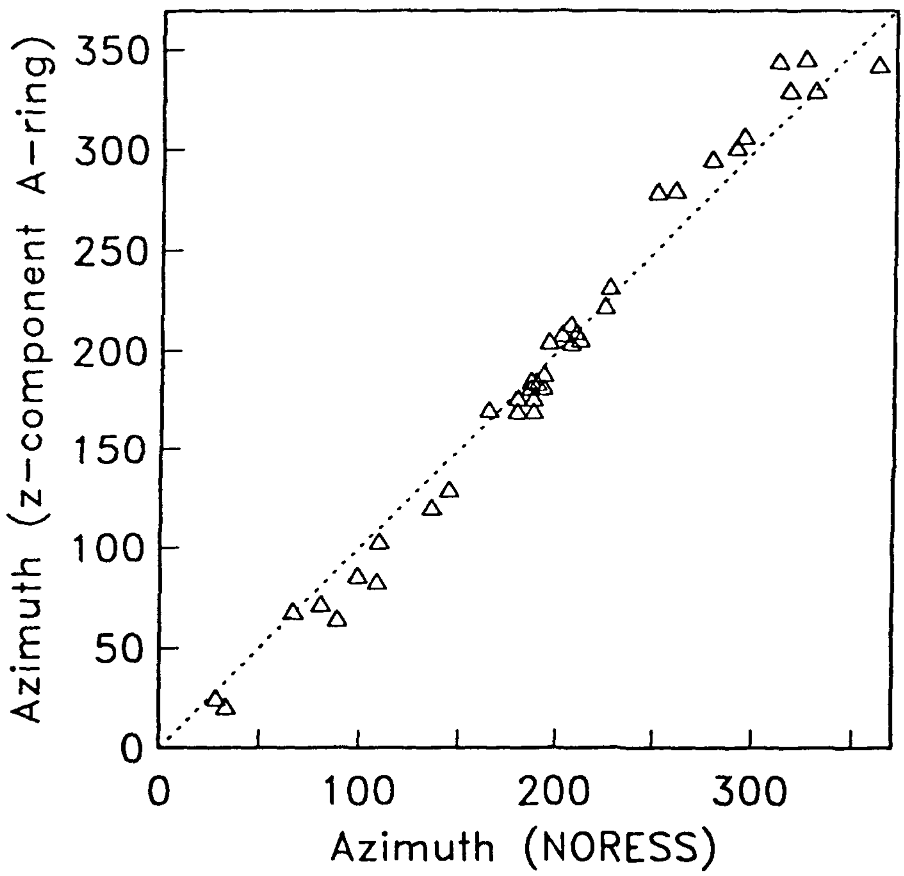


FIG. 3. Comparison of estimated azimuths of P-phases using the NORESS array and the vertical components of the microarray (broadband f-k). The RMS azimuth deviation is 13.7 degrees.

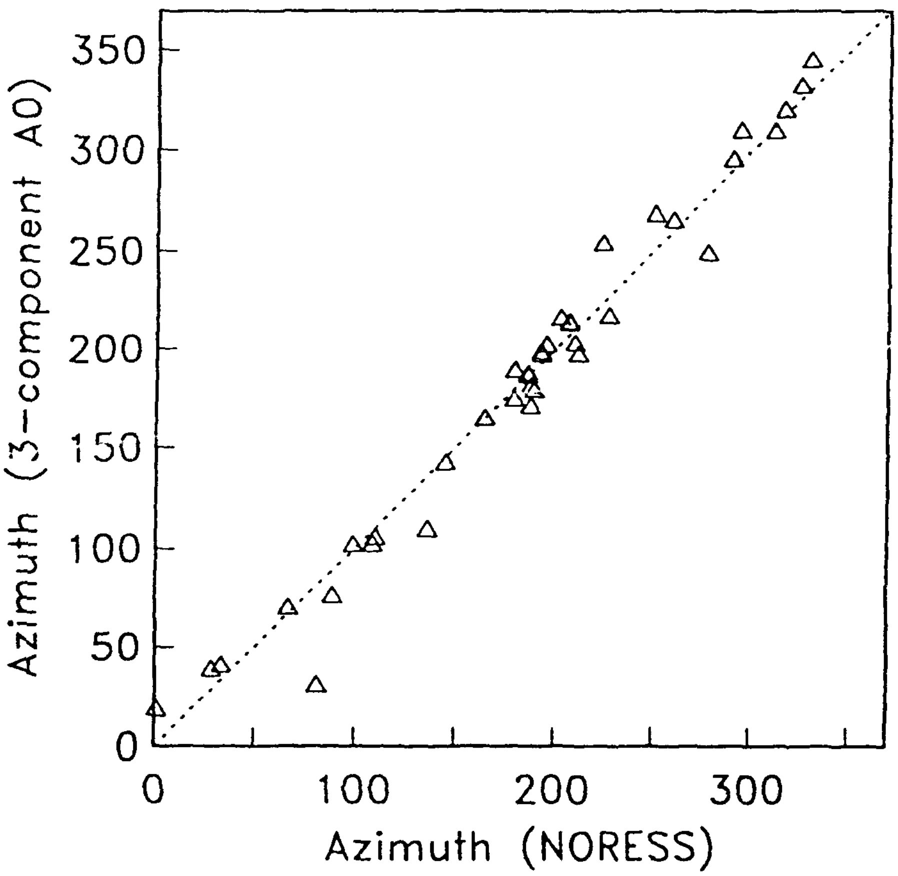


FIG. 4. Comparison of estimated azimuths of P-phases using the NORESS array (broadband f-k) and the A0 three-component system (polarization analysis). Note that the consistency is similar to that of Figure 3, with a RMS azimuth deviation of 14.3 degrees.

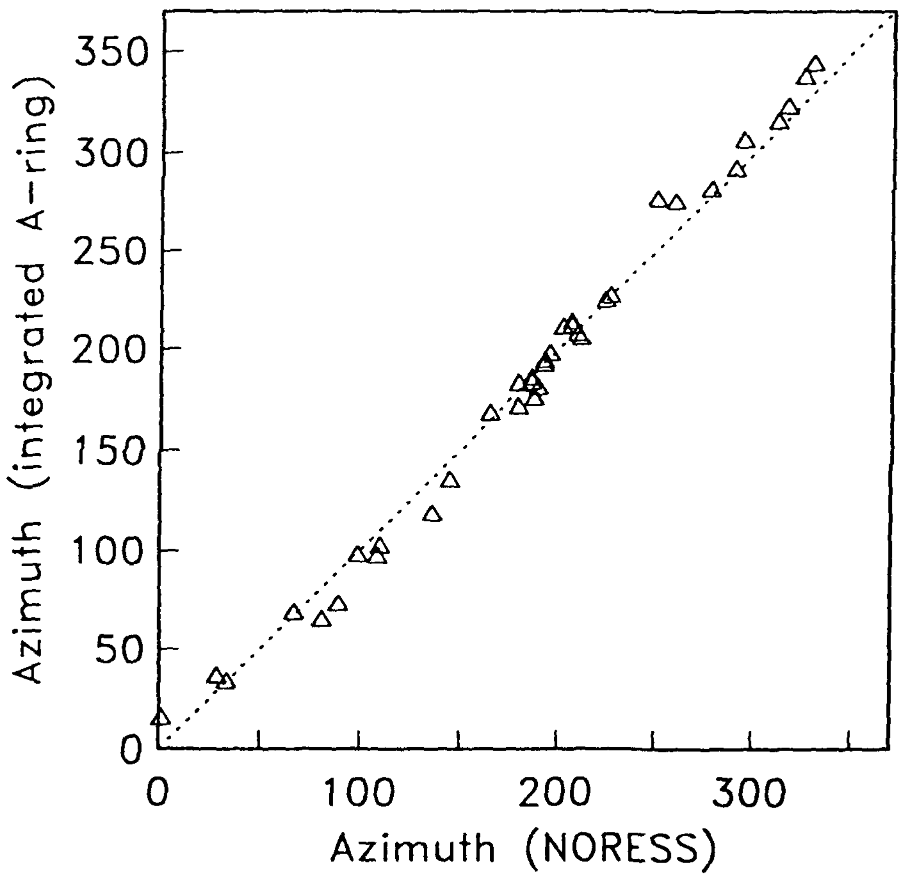


FIG. 5. Comparison of estimated azimuths of P-phases using the NORESS array (broadband f-k) and all sensors in the microarray (integrated f-k processing). The RMS azimuth deviation is 9.6 degrees, i.e. significantly lower than in Figures 3 and 4.

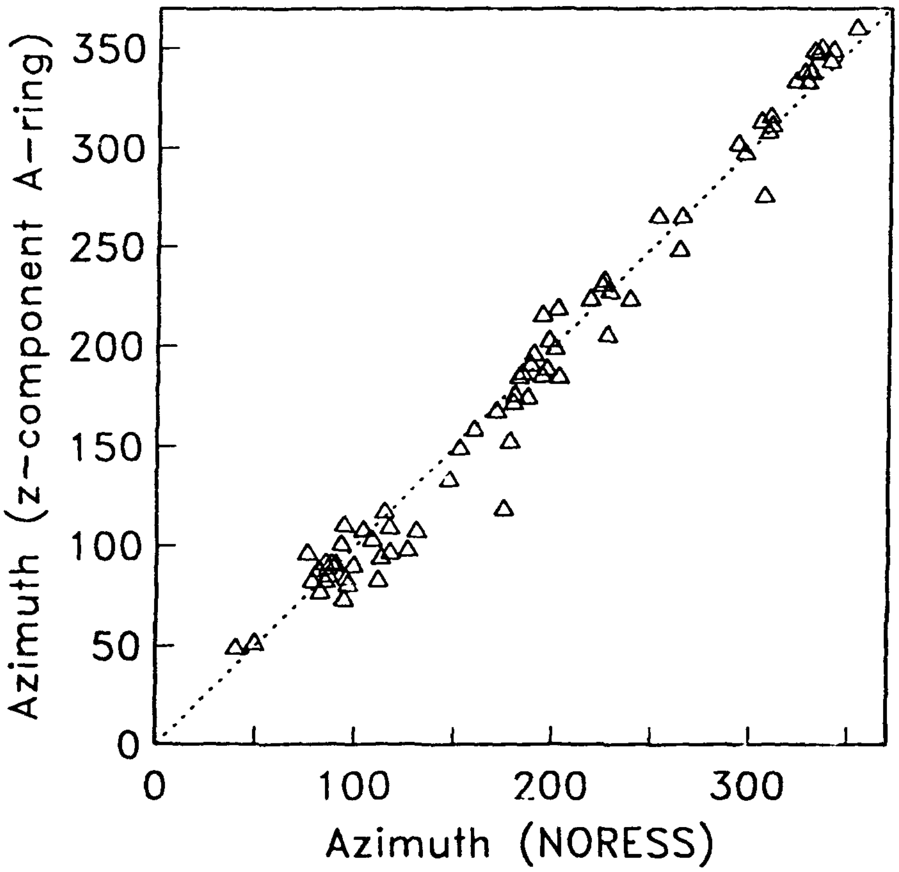


FIG. 6. NORESS and microarray azimuth comparison for S-phases. Note that the consistency is as good as for P-phases (on figure 3), with a RMS azimuth deviation of 13.9 degrees.

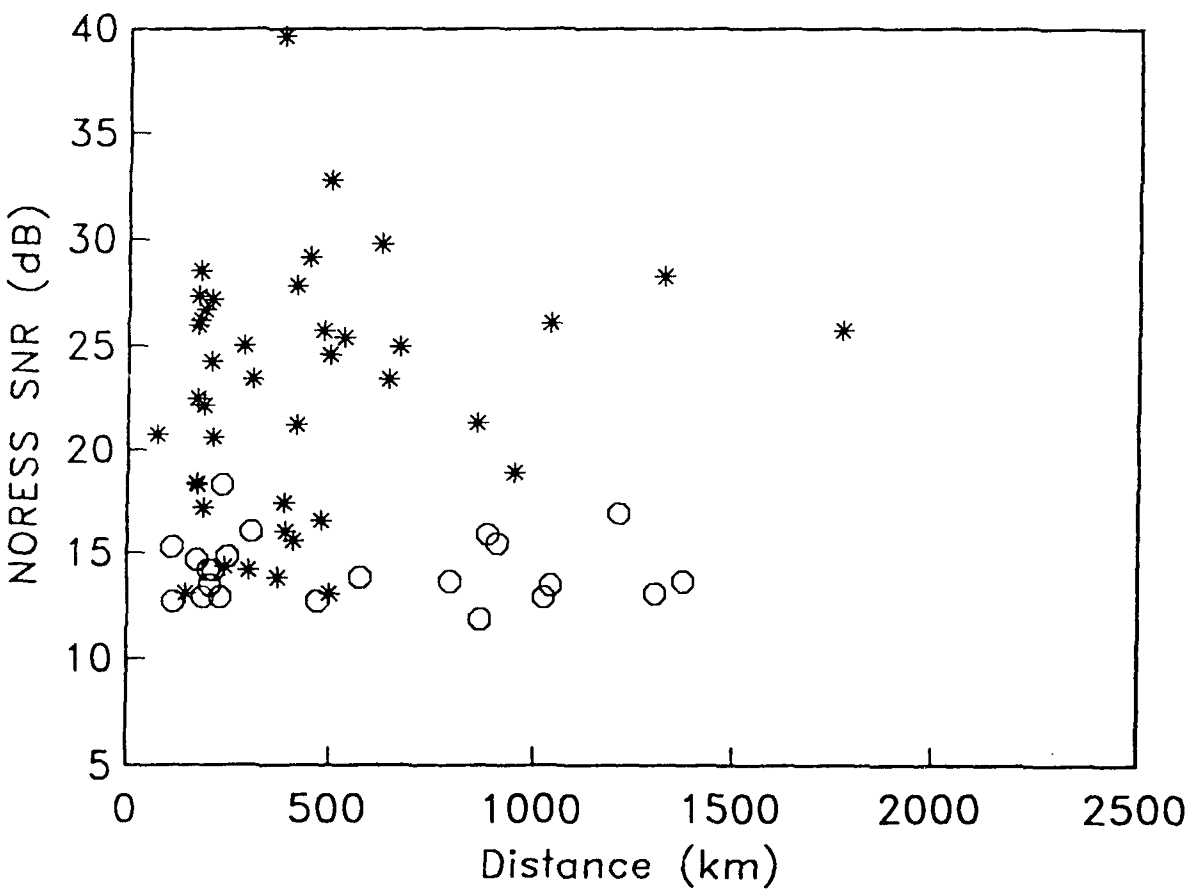


FIG. 7. Illustration of P-phase detectability of the microarray. P-phases detected are marked as asterisks, whereas nondetected phases are marked as circles. Note that the reference array (NORESS) is clearly superior at distances > 500 km.

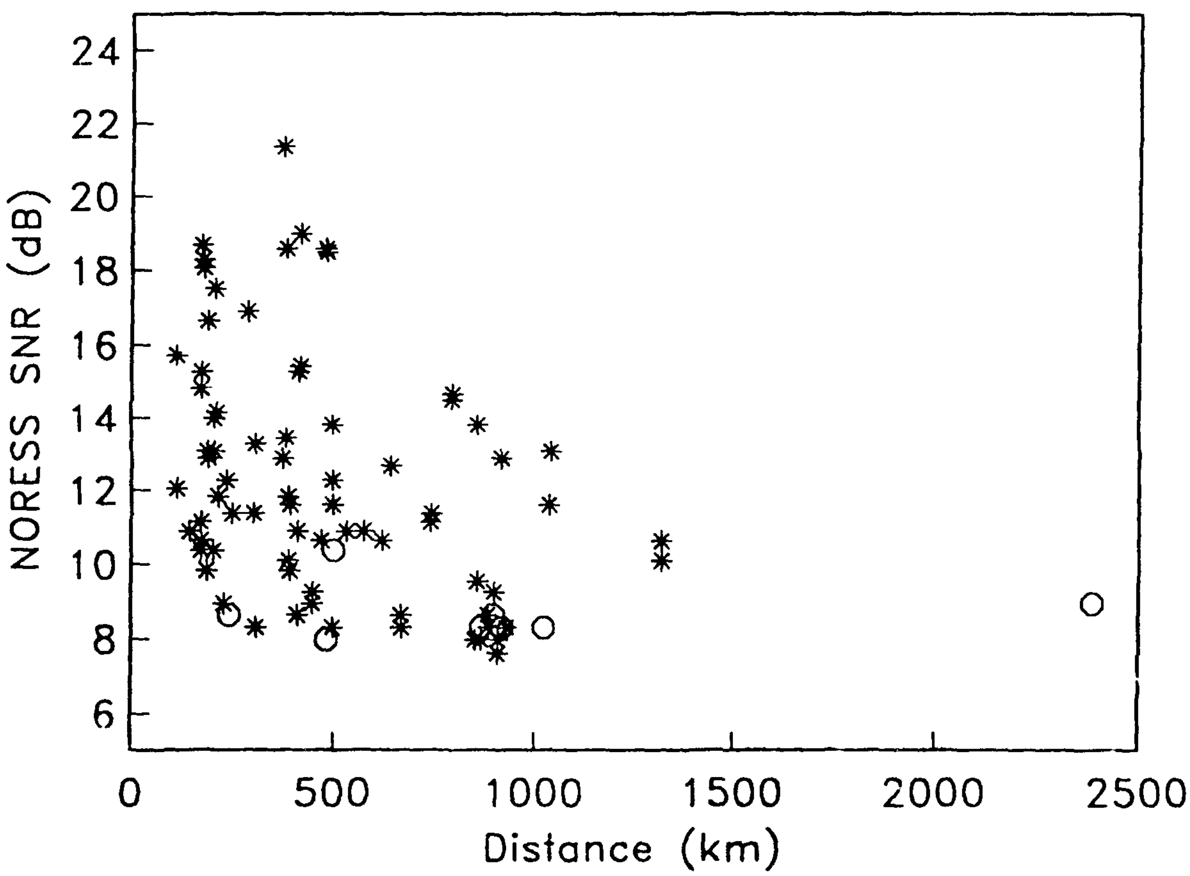


FIG. 8. Same as Figure 7, but for S-phases. Note that in this case the microarray comes close to matching the full array performance.

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